

Scale Dependence of Land Atmospheric Interactions in Wet and Dry Regions as Simulated with NU-WRF over Southwest and Southeast US

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Abstract

Large-scale forcing and land-atmospheric interactions on precipitation in the dry and wet regions in the southwest US and south central US are investigated with NU-WRF simulations during fast transitions of ENSO phases in spring-early summer of 2010 and 2011. The model is found to capture major precipitation episodes in the 3-month simulations without resort to spatial nudging but underestimates the mean intensity compared to observations by 46% and 57% in the dry and wet regions in the southwest and south central US, respectively.

Sensitivity studies with swapped soil moisture show that large-scale atmospheric forcing plays a major role in producing regional precipitation. A methodology to account for moisture contributions to precipitation for individual precipitation events as well as total precipitation in a period as a function of temporal and spatial scales is presented under the same moisture budget framework. The analysis shows that the relative contributions of evaporation and moisture convergence depend on the dry/wet regions and temporal and spatial scales. While the relative contributions vary in the small domains and individual rain episodes, evaporation provides major moisture source in the dry region and light rain events, which leads to greater sensitivity to soil moisture in the dry region and light rain events. The feedback of land surface processes to large-scale forcing is well simulated as indicated by changes in atmosphere circulation and moisture convergence. Overall, our results reveal an asymmetrical response of precipitation events to soil moisture, with higher sensitivity under dry than wet conditions. Drier soil moisture tends to further suppress existing below-normal precipitation via a positive soil moisture-land surface flux feedback that could worsen drought conditions in the Southwest US.

1. Introduction

Precipitation is a critical component of the global water and energy cycle and is one of the most societally relevant aspects of the weather and climate system. The coupling and feedback between soil-moisture and precipitation have been studied extensively in the last several decades (Budyko, Budyko, 1974, Charney et al. 1977, Shukala and Mintz, 1982, Brubaker et al., 1993 and Eltahir and Bras, 1994).

The direct impact of soil moisture to precipitation is through its control on evapotranspiration, i.e., a direct moisture supply to precipitation and associated water recycling (Brubaker et al., 1993 and Eltahir and Bras, 1994; Joussaume et al., 1984, Koster et al., 1986, Dirmeyer and Brubaker, 1999, Brubaker et al., 2001, Bosilovich and Schubert, 2002 and Bosilovich and Chern, 2006). However, soil moisture can also affect many other physical processes, i.e., the surface albedo and partition of surface water and heat fluxes. These can further affect planetary boundary development and moisture convection (Betts and Ball 1998; Eltahir 1998; Notaro et al. 2006; Seneviratne and Stockli 2008; Taylor and Lebel 1998 Dirmeyer et al. 2006; Koster et al. 2004; Meng et al. 2011; Pielke et al. 1999; Santanello et al. 2011; Weaver et al. 2002; Zaitchik et al. 2007). For example, Betts (1998) proposed a positive feedback mechanism through soil moisture impacting the partition of latent and sensible heat flux into the boundary layer. Under his hypothesis, drier soil moisture reduces latent heat flux but increases sensible heat flux, resulting in higher Bowen ratio and lower moisture static energy (MSE), higher boundary layer height and lifting condensation level (LCL) that tends to inhibit the shallow convection. A similar hypothesis is proposed by Eltahir (1998) through modulation of surface net radiation flux.

In addition to the local effect, the large-scale and non-local effect of soil moisture has been found through the impact of large-scale circulation patterns and advection of moisture from one region to another (Shukla and Mintz 1982; Meehl 1994; Douville 2002; Rowell and Blondin, 1990 and Beljaars et al., 1996). But the scale and mechanism for these impacts are still not well understood (Cook et al. 2006).

As discussed above, the soil moisture-precipitation interaction involves many complicated physical processes. The most significant coupling “hot spots” are found in transitional regions where large variations of soil moisture allow its impact on evapotranspiration (Koster 2004). The interaction could take place in two modes: a dynamic mode before and during storm events (storm scale of hours to days) and a slow mode associated with the long-term (months to seasons) variability of precipitation, evaporation, and soil moisture (Barros et al. 2002). Thus, it is important to study the soil moisture - precipitation feedback under given spatial and temporal scales in any regions. In this study, we will review some of the fundamental questions in soil moisture – precipitation feedback, i.e., the relative importance of large-scale forcing and soil moisture in different regions (dry and wet) and different kinds of rain events (light and heavy) under the same moisture budget framework. In particular, we will examine how the results may change with spatial and temporal scales. The study uses NU-WRF simulations of two contrasting years 2010 and 2011 focusing on spring-early summer in the southern US. Section 2 describes model experiments and validation data sets. Section 3 analyzes the model simulation results. Section 4 provides summary and discussions.

2. Data and methodology

1. NU-WRF model

The NASA-Unified WRF (NU-WRF; <http://nuwrf.gsfc.nasa.gov>) modeling system has been developed at Goddard Space Flight Center (GSFC) as an observation-driven integrated modeling system that represents aerosol, cloud, precipitation and land processes at satellite-resolved scales (Peters-Lidard et al. 2015). NU-WRF is a superset of the National Center for Atmospheric Research (NCAR) Advanced Research WRF (ARW) dynamical core model (Skamarock et al., 2008), achieved by fully integrating the GSFC Land Information System (LIS; Kumar et al. 2006; Peters-Lidard et al. 2015), the WRF/Chem enabled version of the Goddard Chemistry Aerosols Radiation Transport (GOCART; Chin et al. 2000) model, the Goddard Satellite Data Simulation Unit (G-SDSU; Matsui et al. 2009) and custom boundary/initial condition preprocessors. Several NASA physical packages have been implemented into NU-WRF, including the cloud resolving model (CRM)-based microphysics (Tao et al. 2003; Lang et al. 2007, 2011, 2014) and radiation (Chou and Suarez 1999) schemes.

In this study, NU-WRF version 3.4.1 (based on NCAR WRF-ARW version 3.4.1) is employed to conduct high-resolution simulations. The model consists 40 vertical levels and two spatial domains with 18 and 6 km grid spacing and time steps of 60 and 20 seconds, respectively. The Grell-Devenyi cumulus parameterization scheme (Grell and Devenyi 2002) is adopted for the outer domain, but the inner domain uses no convective parameterizations. The PBL parameterization employs the Mellor-Yamada-Janjic (Janjic 1994) Level-2 turbulence closure model through the full range of atmospheric turbulent regimes. The Goddard broadband two-stream approach is used for the short- and long-wave radiative flux calculations (Chou and

Suarez 1999) with explicit interactions with clouds (microphysics). The inner domains use the Goddard 3ICE scheme (Lang et al. 2011) that prognoses three types of ice hydrometeor species (i.e. cloud ice, snow, and graupel).

The LIS in the simulation not only provides physically consistent land surface initialization for NU-WRF but also interacts with the surface layer and atmospheric components of NU-WRF that produce coupled water, energy and momentum fluxes. The LSM employed in LIS for this study is Noah LSM version (Ek et al. 2003). It uses the same domain configuration as NU-WRF, providing high-resolution surface initialization with high accuracy (e.g. Case et al. 2011 and Wu et al. 2015). The offline LIS cold started from 1 January 2007 to 19 May 2011 to spin up the land surface states to achieve equilibrium for initialization of WRF-LIS. It uses the North American Land Data Assimilation System (NLDAS) rainfall data (Xia et al. 2012) to provide hourly rainfall and NCEP Global Data Assimilation System (GDAS) to provide atmospheric forcing input.

b. Experiments

The study selects two distinct years of 2010 and 2011 during spring to summer transition time over CONUS to examine the effect of large-scale forcing and land-atmosphere feedback in individual precipitation events as well as total precipitation over a season. We conducted four 3-month simulations with the NU-WRF-LIS system using large-scale forcing and soil moisture of its own (original runs) and the swapped soil moisture (swapped runs) for these two years (Table 1). The combination of these simulations allows us to examine the impact of soil moisture under the same large-scale forcing and large-scale forcing under the same soil moisture condition. The

experiments run from March 20 to June 20, covering transition period from early spring to summer with a significant evolution of soil moisture and atmospheric boundary conditions. A few short-term simulations have also been conducted to examine the impact of different surface models, i.e., NU-WRF-LIS vs. Noah on the results.

c. Validation data sets

Two observational precipitation data sets are used to evaluate the model simulations. One is the precipitation forcing data prepared for the NLDAS (Mitchell et al. 2004). The NLDAS precipitation forcing over CONUS is anchored to NCEP's 1/4th degree gauge-only daily precipitation analyses of Higgins et al. (2000). In NLDAS, this daily analysis is interpolated to 1/8th-degree, and then temporally disaggregated to hourly values by applying hourly weights derived from hourly, 4-km, radar-based (WSR-88D) precipitation fields. The latter radar-based fields are used only to derive disaggregation weights and do not change the daily total precipitation.

The other data set used is the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA; Huffman et al. 2007). The TMPA is a popular satellite-based precipitation product utilizing almost all space-borne precipitation sensors with calibration from TRMM instruments. It combines passive microwave (PMW) precipitation estimates from a variety of low-Earth-orbit satellites and an international constellation of five geostationary satellites, providing multi-satellite precipitation estimates in 3-hourly, $0.25^\circ \times 0.25^\circ$ resolution and quasi-global (50°S – 50°N) coverage. The research version used in this study (3B42) is further adjusted with gauge measurements over the land.

In addition, meteorological fields from NCEP North American Regional Analysis (NARR, Mesinger et al. 2006) are used to examine the atmosphere large-scale and boundary conditions in section 3.1. The NARR model uses the high-resolution NCEP Eta Model (32km/45 layer) together with the Regional Data Assimilation System (RDAS) that assimilates precipitation along with other variables.

3. Results

3.1 Meteorological conditions in the spring 2010 and 2011

ENSO (El Nino Southern Oscillation) is the main driver of interannual variability of precipitation in US (Ropelewski and Halpert 1986, Barnston et al. 1999; Ting and Wang 1997) modulated by decadal scale variability from other climate modes such as PDO (Pacific Decadal Oscillation) and AO/NAO (Annual Model/North Atlantic Oscillation) (Ting and Wang 1997, Higgins et al. 2001; Wang et al. 2013). The springs of 2010 and 2011 are interesting case studies because they represent the fast (intraseasonal) - transitions of ENSO phases. Spring 2010 coincided with a rapid weakening of the 2009-2010 El Nino, which started in May 2009, peaked in late December 2009 and terminated in the first quarter of 2010. By April 2010, the Pacific Ocean had returned to neutral and continued to cool. A La Nino condition started to develop in June 2010, strengthening through the autumn and winter. After reaching the peak around January 2011, it again started to weaken, and by May 2011, had returned to neutral conditions, but lingering La Niña-like atmospheric impacts were still felt in the global Tropics and were mainly responsible for the hot and dry conditions in the southwest US (Wang et al. 2013). Spring 2011 was particularly interesting because many rainfall and drought extremes occurred in the US

during this period. The lower Mississippi River experienced one of the worst floods in recent history due to extreme rainfall in Ohio Valley in late April and early May. In the following, we will show the general meteorological conditions of spring 2010 and 2011 as compared with climatology (based on the period 1979-2013) using the NARR data.

Even though La Nino condition has not formally established till June, the precipitation anomaly from March 20 to June 13, 2010, resembles a weak La Nino condition, with positive anomalies in the northwest and negative anomalies in the southeast (Fig. 1a). During 2011, the negative anomalies extended further westward to Texas and Arkansas (Fig. 1b), showing a much strong influence of La Nino circulation. The soil moisture indicates a very dry year in the south and southeast of US in 2011 (Fig. 1d), with only a small area of positive anomalies in the center of Ohio Valley, which is likely due to the heavy precipitation in this area during later April and early May (Fig. 2b). The soil moisture anomaly in 2010 is mostly positive over the entire CONUS except the northeast. Based on precipitation and soil moisture anomalies in the Texas and lower Mid-west regions in these two years, we broadly categorize 2010 as a wet year and 2011 a dry year.

For the purpose of comparison, we select two regions: one in the mid-west in northern Texas and Oklahoma and the other in the Central Mississippi Valley (boxes in Fig. 1) to represent the dry and wet regions, respectively. These two regions are very sensitive to the location and strength of Pacific jet stream and moisture inflow from Gulf of Mexico (Higgins et al. 1997; Weaver et al. 2002). For the dry region, three relatively large episodes of precipitation events can be seen around April 14, May 15, Jun 14 in 2010, boosting up low precipitation otherwise in the region (Fig. 2a). Soil moisture is slightly above the climatology before June and

decreases to slightly below climatology after June (Fig. 2c). In the wet region, precipitation is close to the climatology for most of the period in 2010, with slightly above normal precipitation during the transition period from middle April to early May (Fig. 2b). The soil moisture is also very close to the climatology in the region (Fig. 2d). In 2011, the precipitation is consistently below the climatology in the dry region due to lack of any significant rain events (Fig. 2a). The soil moisture is much drier than the climatology for the entire period (Fig. 2d). In the wet region, even though soil moisture is much below the climatology, the precipitation is not significantly below the climatology. On the contrary, during the period from April 15 to May 5, there are many episodes of heavy precipitation events in Midwest and Ohio Valley, which led to the worst flood in record history in the lower Mississippi River. The excessive rainfall over northern States especially the Northwest and severe drought in Texas and New Mexico in 2011 are consistent with a typical La Nina condition due to northward shift of the Pacific jet stream (Ting and Wang, 1997; Kumar and Hoerling, 1998).

The soil moisture in the two regions has a clear impact on the surface flux exchange and atmospheric boundary conditions. In the dry region, higher Bowen ratio and planetary boundary layer height (PBLH) are observed in consistent with much drier soil moisture in the spring of 2011 than in 2010 (Fig. 2e and Fig. 2g). Whether the dry soil moisture had further suppressed precipitation in the dry region in 2011 is a question to be answered (Betts 1998; and Eltihar 1998). In the wet region, even though the soil moisture in 2011 is much below its climatology in the region, it is higher than that in the dry region (Fig. 2d). The Bowen ratio in the wet region is much smaller than the dry region and remains close to climatology even though the soil moisture in 2011 is much lower (Fig. 2f). The small variability in Bowen ratio could limit the impact of

soil moisture to precipitation in the wet region. Convective Available Potential Energy (CAPE) is low in the early spring in both regions and increases quickly starting in late April (Fig. 2i and Fig. 2j). In the dry region, CAPE is higher in 2010 than that in 2011, while in the wet region, it is higher in 2011, consistent with the observed precipitation in these two regions.

In the following, we will show the NU-WRF simulations of precipitation in these two seasons. The questions we want to answer are whether and how soil moisture has affected the precipitation in 2010 and 2011 in the dry and wet regions separately? What are the roles of large-scale circulation and moisture convergence as compared with evaporation and soil moisture? What is the scale dependence of land-atmosphere interaction as revealed by moisture budget of precipitation?

3.2 Model simulations of heavy and light rain

Before discussing the sensitivity tests, we will briefly compare NU-WRF simulations with observations to assess the model's capability and limitation in simulating individual precipitation events as well as total precipitation in the 3-month period. Figure 3 shows the accumulated precipitation from the model's original run (driven by the same year large-scale forcing and soil moisture) with the two observational data for the period March 20 to June 13 in 2011. The two observational data sets show similar spatial distributions with a heavy precipitation corridor along the central-east region along the Mississippi valley. The 3B42 misses heavy precipitations in the west coast along the Cascada mountain range. The NU-WRF has roughly captured the spatial distribution of rainfall within the CONUS with large precipitation in the northwest and central northeast and less precipitation in the southwest US. The model tends to overestimate precipitation in the northwest and underestimate in the

southeast and Gulf coast, a feature quite common in Regional Climate Model (RCM) simulations (Mearns et al. 2012). In particular, the model significantly underestimates heavy precipitation in the central-southeast US, which might be due to its poor simulation of upper and lower level jets critical to the moisture convergence in the region (Higgins et al. 1997; Mo and Barbary, 2003). Previous studies indicate that spatial nudging could improve the results by improving the large-scale forcing further into the domain center (Miguez-Macho et al. 2005). However, nudging will essentially eliminate the feedback to the large-scale forcing from land-surface interaction, and thus defy the purpose of this study that aims to understand the mechanism and feedback of land-atmospheric interaction. The possible impact of this model bias in the simulation of heavy precipitation events will be included in the discussion of results.

The domain averaged time series for the wet, and dry regions show that the model captures the main episodes of precipitation and timing long after its initialization time in April and May, but underestimates the intensity of heavy rain (Fig. 4). The skill detracts with longer forecast time and the model misses increasingly more rain episodes entering the second half of June, so the analysis is cut off at June 13. The mean precipitation intensity from NU-WRF for the period March 20 – June 13 is about 54% and 43% (corresponding to an underestimate of 46% and 57%, respectively) of that from NLDAS for the dry and wet regions. While these results are not ideal for quantitative seasonal forecasts, they are comparable with similar studies (Mearns et al. 2012; Bukovsky et al. 2013). Many previous studies have shown that model configurations, i.e., domain size, spatial resolution, nudging, large-scale forcing and physical parameterizations could affect the simulations (Done et al. 2005; Miguez-Macho, 2005), however, it is not the focus of this study to achieve the best model simulations. The impact of

model configuration and physical scheme in short-term simulations will be a discussed in a separate paper.

3.3 Impact of large-scale forcing and soil moisture to precipitation

To understand the effect of soil moisture and large-scale forcing on precipitation, we swapped the large-scale forcing and soil moisture in 2010 and 2011 to produce four simulations (Table 1). It is well expected that large-scale forcing plays a dominant role in the mean precipitation as the difference between the two original runs (S10-org and S11-org) are larger than that between the original and swap runs (S10-org vs. S10-swp and S11-org vs. S11-swp) (Table 2 & 3). In the dry region, there would be a 23% reduction of mean precipitation in 2010 if the drier soil moisture of 2011 were used in the simulation. Likewise, mean precipitation would increase by 23% in 2011 if the wetter soil moisture of 2010 were used (Table 2). On the other hand, the soil moisture has little impact on the mean precipitation in the wet region (Table 3).

The large difference of precipitation in the dry region is supported by the difference in mean atmospheric conditions as shown in Figure 5. In the S11-org simulation, dry soil moisture prevails in the southern US especially in the southwest as compared to the S11-swp simulation (Fig. 5b). This leads to higher sensible heat flux (Fig. 5c) and lower latent heat flux (Fig. 5d) that contribute to higher Bowen ratio (Fig. 5g) and PBLH (Fig. 5f) in the southwest as predicted by Betts (1998). The elevated Bowen ratio and PBHL can be observed in the dry simulations in the entire period especially before precipitation events (Fig. 6). High PBLH is a result of the dry boundary, low equivalent potential temperature and likely more entrainment of dry free atmosphere in the planetary boundary top (Betts and Ball 1996), suppressing convection as a result. On the other hand, the net increase in surface radiation is contrary to reduced net surface

radiation from increased albedo as suggested in Eltahir (1998) (Fig. 5e). One reason could be that the standard Noah LSM does not include a dynamic albedo scheme that changes with soil moisture (Zaitchik et al. 2013), but more importantly, a net increase in surface radiation is mainly due to reduced cloud and precipitation in the drier conditions. Also, lower moisture convergence is simulated in S11-org than in S11-swp in the dry region, indicating a feedback from large-scale circulations has occurred (Fig. 5h).

The relative importance of large-scale forcing and soil moisture is further illustrated in Figure 7. In the top panel, the difference in geopotential height and wind in 850 mb and 200 mb from two simulations (S11-org and S10-swp) with the same soil moisture (2011) are shown. The figure shows low-pressure anomalies in 2011 covering almost the entire CONUS in 850 mb with the exception of southwest and northeast, with a high pressure center located in the mid-west area. This low system deepens in the 200mb where a deep trough extends into the Gulf of Mexico. This circulation pattern directly contributes to dry condition in the southwest and facilitates more moisture being transferred from the Gulf of Mexico, causing heavy precipitation along the upper Ohio valley. The lower panel of Figure 7 shows the circulation difference using the same large-scale forcing (2011) but different soil moisture (S11-org versus S11-swp). It shows that replacing the dry soil moisture (2011) with relatively wet soil moisture (2010) would induce a positive anomaly in geopotential height in the southeast and northwest and a negative anomaly in the southwest and northeast. In the upper atmosphere, the entire CONUS was under positive geopotential height anomaly except in the northwest. This illustrates that the feedback due to soil moisture can affect the circulation, but the impact of soil moisture to circulation is an order of magnitude smaller than the difference introduced by different large-scale forcings.

3.4 Scale dependence

There are many pathways that soil moisture can affect precipitation through evapotranspiration, radiation, boundary layer processes. In the above section, we have shown that soil moisture could affect surface heat flux, planetary boundary layer, and feedback into large-scale circulations. Ultimately, all these effects can be traced back to moisture sources into the precipitation: evaporation, moisture convergence, and moisture storage in the atmosphere. Assuming the liquid and ice water amount from advection of cloud is negligible, the moisture budget equation takes the form (Rasmusson 1968, 1971; Yanai et al. 1973):

$$\langle P - E \rangle = \left\langle \frac{1}{g} \int_s^t \nabla \cdot V q dp \right\rangle + \left\langle \frac{\partial}{\partial t} \frac{1}{g} \int_s^t q dp \right\rangle \quad (1)$$

Here, P , E , V , q , g , and p are precipitation, evaporation, wind, specific humidity, acceleration of gravity and pressure respectively, and $\langle \rangle$ represents time average and $\frac{1}{g} \int_s^t dp$ vertical integration, respectively. The first term on the right side accounts for the horizontal moisture convergence (MCONV) and the second term represents a change of column water vapor in the atmosphere. By tracking the changes in surface evaporation and moisture convergence, we can quantify the net effect of soil moisture to precipitation. However, since precipitation is highly nonlinear and intermittent in nature largely controlled by synoptic-scale forcing, the effect of soil moisture to precipitation will vary significantly for individual precipitation events, as well as the temporal and spatial scales in question (Zangvil et al. 2001). It has been suggested that such moisture budget analysis requires a minimum size of $0.6\text{--}1.0 \times 10^6 \text{ km}^2$ (Rasmusson 1968, 1971; Yanai et al. 1973). In the following, we will illustrate the effects of soil moisture as a function of spatial and temporal scales using a moisture budget

analysis method. We hope to provide a qualitative as well as a quantitative estimate of soil moisture effect under different situations.

3.4.1 Moisture budgets of single rain events

It is well known that water cycles through surface and atmosphere, land and ocean, tropics and Polar Regions. Over a long period (a year and over), the total precipitation will be roughly balanced by total evaporation and ground run-off. From the viewpoint of a single precipitation event, both the atmospheric thermodynamic conditions (boundary instability, CAPE) and moisture supply (pre-stored as soil moisture and precipitable water in the atmosphere) are a result of accumulated meteorological conditions long before the actual event (Trenberth et al. 2003). The pre-storm moisture storages are determined by continuous moisture convergence and surface evaporation before the storm. Therefore, to account for the moisture budget of a precipitation event, it is necessary to define the window of events.

Assuming a precipitation event ends at day-0, if we consider the moisture contribution to the event starts from d-days before (designated as $-d$) regardless of its actual starting time, the moisture budget for this particular event is thus an integration from day $-d$ to 0 and a function of d (Figure 8):

$$AV_{-d} = AV_{-d \rightarrow 0} = \sum_{t=-d}^0 V_t \quad (2)$$

This is equivalent to consider the precipitation event in a window-size of d-days. Here A represents accumulation over the time period. The parameter V can be precipitation (PREC), moisture convergence (MCONV) and evaporation (EVAP). The moisture budget terms and their

relative contributions are obviously a function of the window size d . The smaller d value (closer to the right end of the x-axis) indicates a smaller window of consideration before the rain event.

Figure 8 shows the integrated moisture budget leading to the heaviest rain event as a function of the leading time during the simulation period in 2010 in the wet and dry regions, respectively. In the wet region, there are several lighter rain events occurred during the 40-day period before the heaviest rain event (Fig. 8a). This figure shows that if we consider the rain event as a 40-day process, total evaporation accumulated during this period is larger than the total moisture convergence during this period. The total evaporation (black lines) decreases steadily as the window size decreases. The total moisture convergence (light blue lines), however, are not a monotonic increasing or decreasing curve with the window size as moisture can converge or diverge out of the region during a given period. They are likely to increase before a major rain event and then decrease after the rain event. Close to the precipitation event (1-2 days leading time), the moisture convergence is found to be much larger than the evaporation. For a medium size window (up to 12 days), it can be seen that the combined evaporation and moisture convergence roughly balances the precipitation, as the period in consideration gets longer, precipitation is slightly less than the summation of evaporation and moisture convergence. A small deposit could be within precipitating clouds that haven't yet rained out, but mostly because the atmosphere can hold more precipitable water as temperature warms up during the late spring and early summer.

In the dry region, we notice a quite different scenario. Before the rain event on May 16, 2010, there are few light precipitation events (Fig. 8b). Evaporation and moisture convergence nearly cancel each other for the longer period, as basically evaporation provides the moisture

source to be divergent out of the region. The moisture convergence could still be a major moisture source in a short term for a major rainfall event, when AMCONV is much larger than AEVAP term on 3~1 days before the event. Inspecting other light events, we found that ACONV could be less than AEVAP even in near term (Figures not shown). Without a sudden source of moisture convergence, precipitation occurs by depleting precipitable water stored in the atmosphere, with a relatively lower rain rate than the event on May 16, 2010.

Replacing the relatively wet soil moisture in 2010 (solid line) with dry soil moisture in 2011 (dash line), we notice larger differences in both evaporation and moisture convergence in the dry region (Fig. 8b) than in the wet region (Fig. 8a). Dry moisture has resulted in less evaporation, and correspondingly, less moisture divergence. The effect to a single precipitation event is also noticeable, as there appears to be a small reduction of rain intensity on May 16, 2010.

3.4.2 Dependence of moisture budget on temporal scale

To examine the cumulative effect on total precipitation in the region, we integrate the three water budget terms (precipitation, moisture convergence, and evaporation) from the beginning of the period to the end. The values in a given day d in Figure 9 and 10 are computed as:

$$AV_{1 \rightarrow d} = \sum_{t=1}^d V_t \quad (3)$$

For the wet region, we notice a steady increase of total moisture from evaporation as the integration days increase, the total moisture convergence increases slightly at the beginning but drops following the rain events (Fig. 9). There was a major jump around April 30 in 2010, and

April 26 in 2011 respectively, slightly ahead of major rain events, and a decrease afterward into negative values by the end of the period. It is tempting to conclude that for periods longer than 60 days, local evaporation (and recycling water vapor) provides the major moisture supply for the total precipitation. However, the exact temporal scale required will depend on the season and region of interest. Furthermore, even though evaporation provides the major moisture supply in the long period, the difference due to surface soil moisture is minimal to the total evaporation and precipitation in this case.

In the dry region, total evaporation steadily increases with time as well, albeit only half the rate as compared with the wet region (Fig. 10). The moisture convergence accumulates in a steady negative direction (which indicates divergence out of the region), with a small upward bump around May 14, 2010, that is also noticeable in total precipitation accumulation. It can be easily noticed the relatively large differences in evaporation and moisture convergence from the swapped soil moisture runs. The dry soil moisture (dashed lines) leads to less evaporation, less divergence (due to lower precipitable water vapor and weaker moisture inflow along the central south US) and a net reduction in total precipitation (Table 2). More importantly, these differences accumulate with time. This illustrates an important positive feedback in the dry region as previously reported (Shukla and Mintz, 1982, Eltahir 1998).

3.4.3 Dependence of moisture budget on spatial domain

The high spatial inhomogeneity of precipitation events prompts another necessity when considering the moisture budget, i.e., selection of domain size and location. A domain chosen inside of a heavy rain event or a large domain encompassing surrounding areas are likely to

come up with a different the moisture budget. Here, we examine the relative contribution of moisture convergence and evaporation to precipitation as a function of domain size in wet and dry regions, respectively. The period considered is the entire simulation period as the results for a short period could vary significantly with individual events and the center of the domain selected.

Figure 11a shows the domain mean total precipitation during the period March 20 to June 13 in the dry region from all four simulations. The domain size increases from $0.25^\circ \times 0.25^\circ$ to $8^\circ \times 8^\circ$ grid boxes with all of them centered on (100°W , 35°E). The general increase of mean precipitation with domain size indicates the center grid box to be the driest spot in this area. Larger differences in precipitation are found between runs with different large-scale forcings (i.e., black versus red lines); smaller but distinctive differences are found between runs with different soil moisture (i.e., solid lines versus dashed lines). These results again show that the large-scale forcing dominates precipitation distribution, but the impacts of soil moisture in both years are obvious. In both years, using drier soil moisture of 2011 has resulted in less precipitation, but the impact is not equal in the two years. The drier year 2011 shows a smaller reduction of precipitation due to dry soil moisture. This is likely due to saturation effect as mentioned in other studies (Seneviratne et al. 2006, Guo and Dirmeyer, 2013, Lintner et al. 2013). When it is already very dry or wet, there is less room to be even more drier or wetter.

To further examine the relationship of these moisture terms, we computed the ratio of evaporation to precipitation (E/P) and moisture convergence to precipitation (C/P), respectively as a function of domain size for all the four simulations (Fig. 11b). The E/P ratio starts at around 4 for the $1^\circ \times 1^\circ$ degree box and asymptote to about 2 for $8^\circ \times 8^\circ$ degree box in 2011. The E/P value

starts with slightly less 2 and remains quite stable at 2 for all domain sizes in 2010. The C/P ratio has comparable magnitude but with negative sign due to net moisture divergence in the dry region. Due to the large ratios of E/P and C/P, it is easy to consider precipitation as a small residue of evaporation and convergence, with the drier year of 2011 more so than the relatively wet year of 2010. The E/P ratios from simulations with drier 2011 soil moisture (S11-org and S10-swp) are slightly smaller than the simulations with wet soil moisture in the corresponding year (S11-swp and S10-org, respectively). This increase in precipitation efficiency partially cancels out the positive feedback due to dry soil moisture (i.e., drier soil moisture-> less total evaporation-> less precipitation->more drier soil moisture). The reduced magnitude of C/P could be simply due to less available moisture to be divergent out of the domain. However, it could also be due to circulation feedback as shown in Figure 7. Obviously, the reduction is not able to completely cancel out the reduced evaporation. Hence, a net reduction in precipitation has occurred.

Spatially, there is a tendency for the simulations from different large-scale forcings to merge as the domain size increases. However, the difference due to different soil moisture tends to increase. This indicates the fundamental role of soil moisture in determining the precipitation recycling in the dry region. The dry soil moisture tends to modulate the precipitation recycling efficiency in the dry region but was not enough to reverse the overall positive feedback in the dry region.

4. Summary and discussion

In this study, we conducted NU-WRF simulations of precipitation events during spring-early summer of 2010 and 2011 in CONUS and examined the impacts of large-scale forcing and land-atmospheric interactions on precipitation in the dry and wet regions in the southwest US and south central US. Both springs are under fast transitions of ENSO phases: from El Nino to La Nino in 2010 and from La Nino to ENSO-neutral in 2011, which typically have large influences on precipitations in these two regions. Even though much extreme rainfall hit Midwest and Ohio Valley in the late April and early May in 2011, based on soil moisture and total precipitation during the entire period, 2010 is wetter than 2011 in both focus regions.

The NU-WRF simulations overestimate precipitation in the northwest and underestimate in the southeast. It captures major precipitation episodes in the study domains but underestimate the mean and peak rain intensity. The simulated mean intensities for the period March 20 –June 13, 2011 measure about 54% and 43% of the NLDAS observations in the dry and wet regions, respectively, possibly due to long integration, lack of spatial nudging, and misrepresentation of upper and lower level jets.

Sensitivity studies of spring 2010 and 2011 with swapped soil moisture show that large-scale atmospheric forcing plays a major role in producing regional precipitation. Soil moisture has a larger impact in the dry region where drier soil moisture in 2011 tends to further reduce the precipitation by approximately 23%, a positive feedback that could worsen the drought in Texas and lower mid-west regions, exacerbating La Nina conditions. It is found that drier soil moisture not only reduces total evaporation through prolonged period over a large spatial domain, but also leads to higher Bowen ratio and planetary boundary height, indicating a potential pathway of positive feedback in the dry region as suggested by Betts et al. 1997. The study also shows the

asymmetric nature of soil moisture impact, with larger impacts found on dry region and light rain events rather than the wet region and heavy rain events. This is consistent with findings from global modeling studies that show most significant coupling of soil-moisture and precipitation occurs in transitional regions with modest rain amount and large variations of soil moisture (Koster 2004).

The sensitivity of precipitation to soil moisture can be analyzed with moisture budget in the atmosphere. We designed a methodology to account for moisture contributions to precipitation for individual precipitation events as well as total precipitation as a function of temporal and spatial scales under the same moisture budget framework. The analysis shows that the relative contributions of evaporation and moisture convergence depend on the dry/wet regions and temporal and spatial scales. While the relative contributions vary in a small domain and individual rain episodes, evaporation provides major moisture source in the dry region and light rain events, which leads to greater sensitivity to soil moisture in the dry region and light rain event. The feedback of land surface processes to large-scale forcing is also noticed through changes in atmosphere circulation and moisture convergence.

We should note that the results from this study depend on current model formulation and physics. As evident in the considerable dry model bias for heavy precipitation events, it is highly possible that the current model physics have not taken into account other important processes, such as the dynamics of the upper and lower level jets, the albedo dependence on soil moisture, etc. (Hong, S. -Y and H. -L. Pan, 1998; Barros and Hwu, 2002, Seneviratne et al. 2013). The lack of response to soil moisture in wet region may be related to the problem of the model

underestimating the magnitude of heavy rain. Hence results shown in this work on soil moisture feedback can only be considered tentative, and need to be validated with more case studies and model intercomparison studies.

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